64-WA/RP-2

QU/83

Printed in U.S.A.

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Mechanical Design and Notch Sensitivity of Molding Materials

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Failures of plastics, particularly molded parts, frequently initiate at discontinuities in the structure, such as holes and notches. To alleviate this problem, the engineer frequently designs the part with large radii, or uses a highly ductile material. Little attempt has been made to determine how plastics behave under conditions of concentrated stress. This paper discusses an experimental technique and results obtained on several polymers.

Contributed by the Rubber and Plastics Division for presentation at the Winter Annual Meeting, New York, N. Y., November 29-December 4, 1964, of The American Society of Mechanical Engineers. Manuscript received at ASME Headquarters, October 7, 1964.

Written discussion on this paper will be accepted up to January 10, 1965.

Copies will be available until October 1, 1965.

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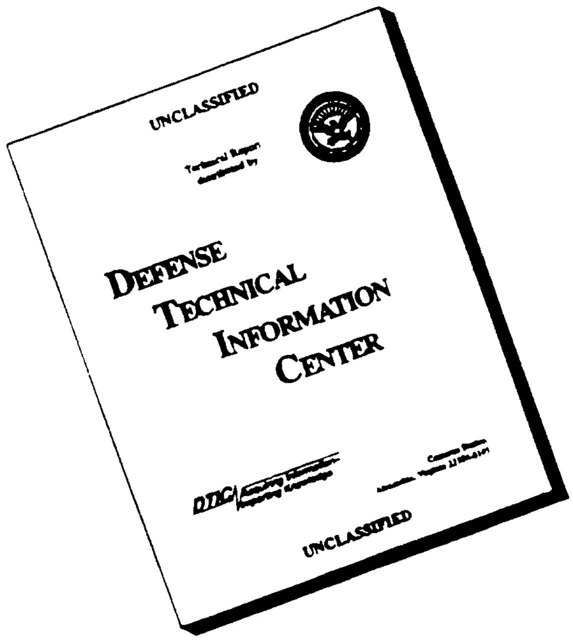

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Mechanical Design and Notch Sensitivity of Molding Materials

C. F. BALAZS

Polymeric materials may be classed as either ductile or brittle at room temperature. A ductile material will fail by undergoing plastic flow, and is typified by high elongation, while a brittle material will fail by a cohesive break, and is typified by low elongation. Plastic flow of the ductile failure is propagated by shear forces, and a shear failure is generally observed. To classify the type of failure correctly one would obtain in a specific application, the conditions of application must be considered. Time, temperature, and environment affect the ductility, stiffness, and strengths of all materials. Plastics materials are likewise affected, and are generally more sensitive to these variables than are metals.

Raising the temperature of a polymer permits the long molecular chains to move more freely past one another, as well as to uncoil when a stress is imposed on them. An elevated temperature generally lowers the modulus of the material, and lowers the tensile strength. Lowering the temperature tends to lock the molecules in place, mitigating flow, and thus resulting in brittle failure. When discussing temperature effects, it is customary to relate them to the location of the glass transition temperature of the polymer. This is the temperature at which the interatomic restraints are sufficiently reduced to permit a large number of relative, nonelastic displacements of neighboring molecules under an applied stress.

Elevated temperatures also change the material properties by permitting crystal growth, as in the case of polyolefins, or deorientation as in the case of heat shrinkable films.

The effect of time is closely related to that of temperature. A failure caused at room temperature and high strain rates will resemble in properties a failure produced at conventional low strain rates, but at low temperatures. The same relationship holds between low strain rates, as in creep, and high temperature tensile testing. A correlation has been made between time, and temperature which allows the superposition of data obtained at various temperatures in short periods of time, to a single desired temperature for long periods of time (1, 2).[1]

Thus either brittle or ductile failures may be caused in the same thermoplastic material by changing the testing conditions or more important the operating conditions of the finished part.

The effect of environment plays an important role in the ultimate properties of polymers (3). The effect of many organic liquids, for example, is to plasticize the polymer, reduce ultimate tensile strength and modulus, and increase ductility. The effect of environment was not a part of this study.

STRESS CONCENTRATIONS

Most failures of molded parts may be shown to have originated from an area of high stress concentration such as a hole, thread, groove, or scratch. Within these areas of high stress concentrations, the stress cannot be calculated in the conventional manner of stress analysis. The stress in these areas is greater than basic strength of materials equations would lead one to expect. In addition to the change in amount of stress, a change in the state of stress near the discontinuity is realized. The uniaxial load which may be applied will cause a biaxial, or triaxial stress state to exist. The presence of these combined stresses influences the yield and ultimate properties of the material more extensively than one would predict in a uniaxial stress state (4); and, since an equilateral biaxial stress pattern will not have a shear component (in the plane of the two principal stresses) flow will not take place and the material will fail in a brittle manner. Generally, the principal stresses are not equal and a shear component is present.

Thus, there are two distinct aspects of stress concentrators; namely, (a) the increase in the stresses produced, and (b) the influence of the combined stresses on the properties of the material.

Values of theoretical stress-concentration factors for specific geometries, readily available in the literature, are obtained by either theoretical calculations, or experimental methods. The stress-concentration factor is defined as the maximum stress in the member, divided by the nominal average stress as derived from the usual strength equations.

The damaging effect of a stress concentration is greater in a brittle material, than in a duc-

[1] Numbers in parentheses designate References at the end of the paper.

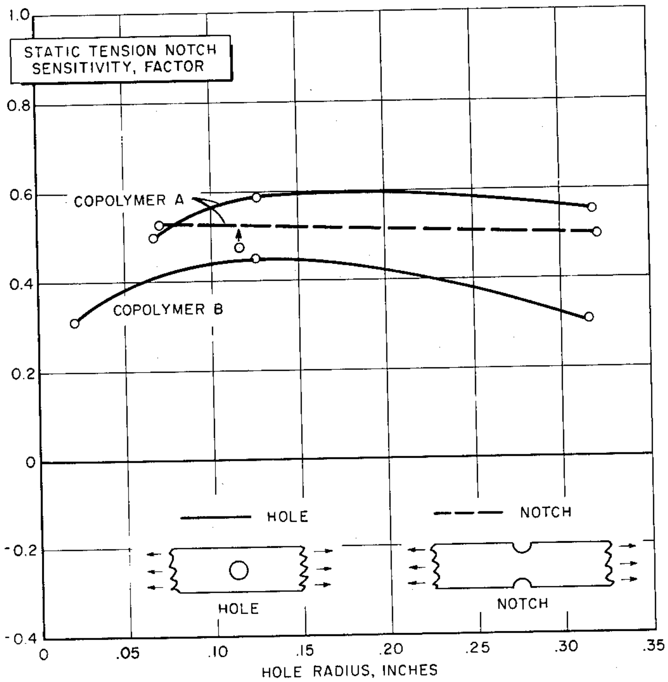

Fig. 1 Notch sensitivity of styrene acrylonitrile copolymers at 73 deg F

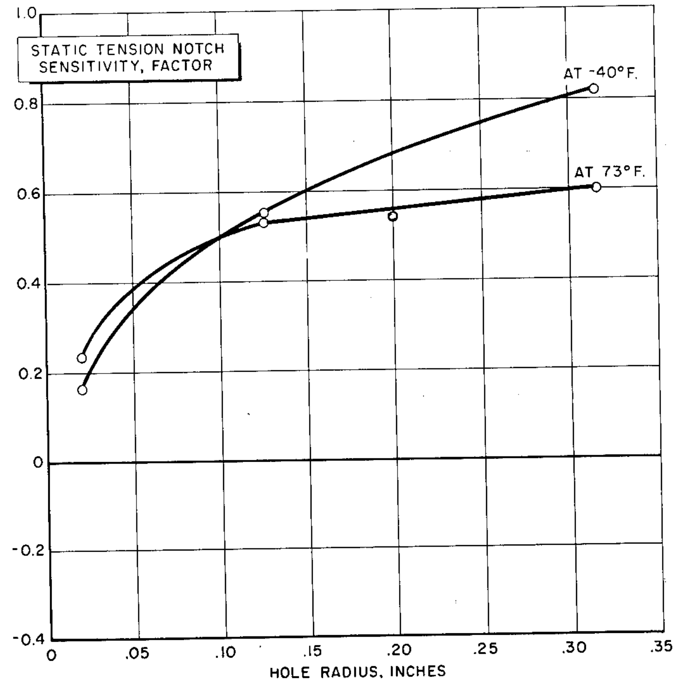

Fig. 2 Notch sensitivity of general purpose polystyrene C at two temperatures

tile material. In ductile materials the stress distribution at the discontinuity changes after the stress exceeds the yield stress. Once the yield stress is reached, further increase in load produces an increase in strain without an accompanying increase in stress. The load is then picked up by the area next to the yielded area. This transfer of load takes place until the stress is distributed away from the discontinuity. If the material is highly ductile, yield will take place across the entire part. Thus the stress concentration is reduced to zero. Brittle materials do not have the ability to redistribute the load, and the stress concentration builds up until the ultimate strength of the polymer is reached. When the ultimate strength is reached a crack initiates and leads to catastrophic failure. The effect of stress concentrators is therefore of most importance in brittle materials, and in those ductile materials which behave in a brittle manner at low temperatures, at high strain rates, or when biaxially stressed.

NOTCH SENSITIVITY

The notch sensitivity of a material is the degree to which the stress-concentrating effect is actually obtained in the material. Peterson (5) defines a notch sensitivity index in fatigue as:

$$q = \frac{k-1}{K-1}$$

where q = notch sensitivity and ranges from zero to one.

$$k = \frac{S}{S'} = \frac{\left[\begin{array}{c}\text{endurance limit}\\ \text{(without stress concentrator)}\end{array}\right]}{\left[\begin{array}{c}\text{endurance limit}\\ \text{(with stress concentrator)}\end{array}\right]}$$

$$K = \frac{\text{maximum stress}}{\text{average nominal stress}}$$

For the purposes of our work we have defined a notch-sensitivity index in static tension as follows:

$$q' = \frac{K_r-1}{K_t-1}$$

where

K_r = strength-reduction factor

$= \dfrac{\text{tensile strength unnotched}}{\text{tensile strength notched}}$

K_t = theoretical stress-concentration factor

The value of q' is the extent that the theoretical stress concentrator affects the specimen when loaded in tension. The stress concentration

Table 1

Radius, In.		Temp.	Ultimate Tensile Strength	K_r	K_t	q'
Notch	Hole	°F	psi			
		Styrene-Acrylonitrile Sample A				
Control	Control	73	7200	-	-	-
-	.063	73	4050	1.78	2.55	0.50
-	.126	73	4000	1.81	2.35	0.60
-	.317	73	4500	1.60	2.05	0.57
.070	-	73	4150	1.73	2.37	0.53
.116	-	73	4650	1.56	2.16	0.48
.320	-	73	6400	1.13	1.25	0.52
		Styrene-Acrylonitrile Sample B				
Control	Control	73	7800	-	-	-
-	.02	73	4900	1.59	2.90	0.31
-	.125	73	4900	1.59	2.32	0.45
-	.315	73	5700	1.37	2.20	0.31
		Polystyrene G.P. Sample C				
Control	Control	73	6700	-	-	-
-	.020	73	4600	1.45	2.90	0.24
-	.125	73	3900	1.72	2.35	0.53
-	.200	73	4100	1.64	2.19	0.54
-	.314	73	4100	1.63	2.05	0.60
Control	Control	-40	8200	-	-	-
-	.02	-40	6300	1.30	2.85	0.16
-	.125	-40	4700	1.74	2.35	0.55
-	.315	-40	4400	1.86	2.05	0.82

All specimens tested on Instron testing machine at a crosshead speed of .05"/minute using a jaw span of 4.5 inches.

factor (K_t) is independent of the material; and is only a function of geometry.

EXPERIMENTAL

Several Dow molding resins were selected for this work on the basis of their degree of ductility. It was desirable to use materials with large differences in ductility to obtain information on the effect of ductility, as measured by Izod impact or tensile test, on notch sensitivity. It was also desirable to measure notch sensitivity of materials which showed no difference in Izod impact strength, but in which customer experience showed differences did in fact exist.

Strain rate was based on the crosshead travel and total gage length. Actual strain rate at the reduced cross section was higher because the stress was higher in this region due to the difference in cross-sectional area. Instrumentation is presently being constructed to measure the actual strain rate at the reduced section.

Specimens were cut from compression-molded sheets, and were then machined into dumbbell test bars having approximate cross sectional dimensions of 0.125 in. x 1.00 in. in the test area. Each

Table 2

Radius, In.		Temp.	Ultimate Tensile Strength	K_r	K_t	q'
Notch	Hole	°F	psi			
		Polystyrene G.P. Sample D				
Control	Control	73	5100	-	-	-
-	.020	73	3450	1.48	2.85	0.26
-	.064	73	3350	1.51	2.54	0.33
-	.128	73	3250	1.58	2.35	0.43
-	.191	73	3300	1.55	2.25	0.44
-	.254	73	3450	1.48	2.15	0.42
-	.330	73	3500	1.45	2.05	0.43
.059	-	73	3100	1.65	2.50	0.43
.119	-	73	3250	1.56	2.15	0.49
.249	-	73	4000	1.27	1.55	0.49
Control	Control	125	4000	-	-	-
-	.020	125	2800	1.43	2.85	0.23
-	.125	125	2300	1.74	2.35	0.55
-	.314	125	2500	1.60	2.05	0.57
Control	Control	-40	8200	-	-	-
-	.068	-40	4950	1.65	2.50	0.40
-	.195	-40	4800	1.71	2.20	0.59
-	.316	-40	4900	1.67	2.04	0.65

All specimens tested on Instron testing machine at a crosshead speed of .05"/minute using a jaw span of 4.5 inches.

Table 3

Radius, In.		Temp.	Ultimate Tensile Strength	K_r	K_t	q'
Notch	Hole	°F	psi			
		Polystyrene H.I. Sample E				
Control	Control	73	3320	-	-	-
-	.064	73	3630	0.915	2.55	-0.055
-	.126	73	3610	0.917	2.37	-0.061
-	.316	73	3640	0.912	2.08	-0.081
.083	-	73	3590	0.925	2.35	-0.056
.113	-	73	3730	0.890	2.20	-0.092
.311	-	73	3880	0.856	1.30	-0.480
		Polystyrene H.I. Sample F				
Control	Control	73	2400	-	-	-
-	.063	73	3150	0.768	2.55	-0.150
-	.125	73	3300	0.730	2.36	-0.200
-	.250	73	3050	0.790	2.15	-0.180
.088	-	73	3400	0.710	2.35	-0.250
.145	-	73	3400	0.710	2.06	-0.270
		Polystyrene M.I. Sample G				
Control	Control	73	3800	-	-	-
-	.02	73	4500	0.850	2.85	-0.08
-	.314	73	4300	0.885	2.02	-0.113

All specimens tested on Instron testing machine at a crosshead speed of 0.2"/minute using a jaw span of 4.5 inches.

test bar was then drilled carefully in the center of the test area, or notched on both sides of the

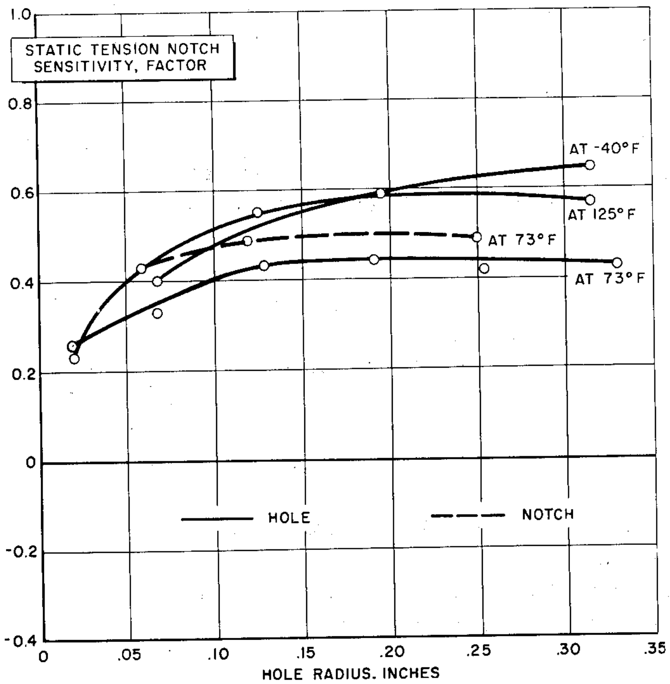

Fig. 3 Notch sensitivity of general purpose polystyrene D at three temperatures

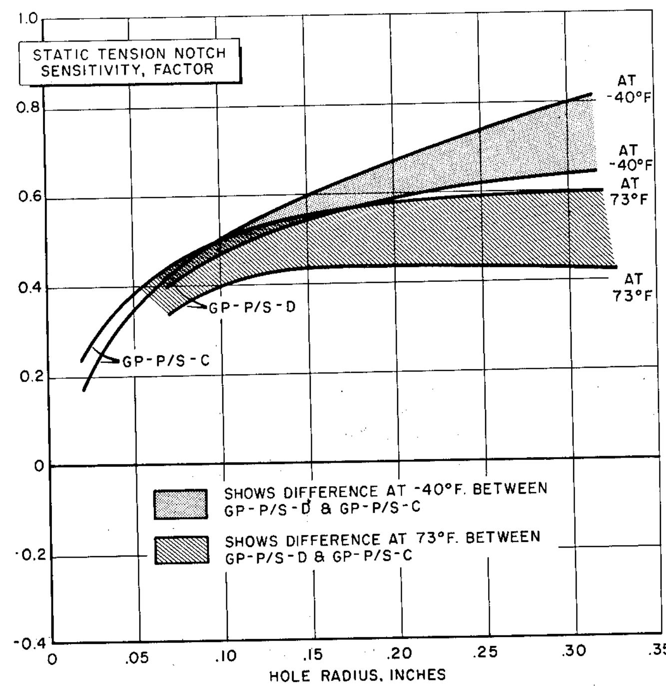

Fig. 4 Comparison of two general purpose polystyrenes at two temperatures

test area, Fig. 1. Initially five specimens at each test condition were run, but good reproducibility of results permitted lowering this to three specimens. Several sets of specimens having differently dimensioned holes or notches were prepared from each material, Tables 1, 2, and 3.

During the preparation of these specimens special care was taken to insure that no extraneous stress raisers were introduced. Any imperfection in the notch or hole, such as a drill nick or chip would introduce error in the calculated effect on the discontinuity. New drill bits were therefore used to insure that a clean cut would be made. Heat buildup during the drilling or notching process was prevented by using a hand operated drill.

The test bars prepared in this manner were tested in an Instron Model TTB universal testing machine, along with unnotched control specimens. Tensile tests were performed at conventional crosshead speeds for the materials. The rupture strength, based on remaining cross sectional area was used to calculate the strength reduction factor (K_r) as follows:

$$K_r = \frac{S'}{S_o}$$

where

S' = tensile strength at rupture of unnotched specimen

S_o = tensile strength at rupture of notched specimen

Notch sensitivity (q') was then calculated as

$$q' = \frac{K_r - 1}{K_t - 1}$$

Results of these studies are shown in Figs. 1 through 5.

DISCUSSION OF RESULTS

Figs. 1 through 5 show the degree of notch sensitivity (q') exhibited by the various materials investigated as functions of the discontinuity imparted to them. The strength-reduction factors (K_r), stress-concentration factor (K_t), notched and unnotched strengths, and notch sensitivity factors are given in Tables 1 through 3. Specimens were investigated with circular discontinuities centrally located, as well as specimens with semicircular notches on the sides, Fig. 1.

Fig. 1 shows the notch sensitivities of two styrene-acrylonitrile copolymers at 73 F. Copolymer A is higher in styrene content and is more notch sensitive than copolymer B. Notch sensitivity is a function of geometry as well as material, and is lowest for small discontinuities.

Fig. 2 shows the notch sensitivity of a general purpose polystyrene at two temperatures. The sensitivity at the low temperature (-40 F)

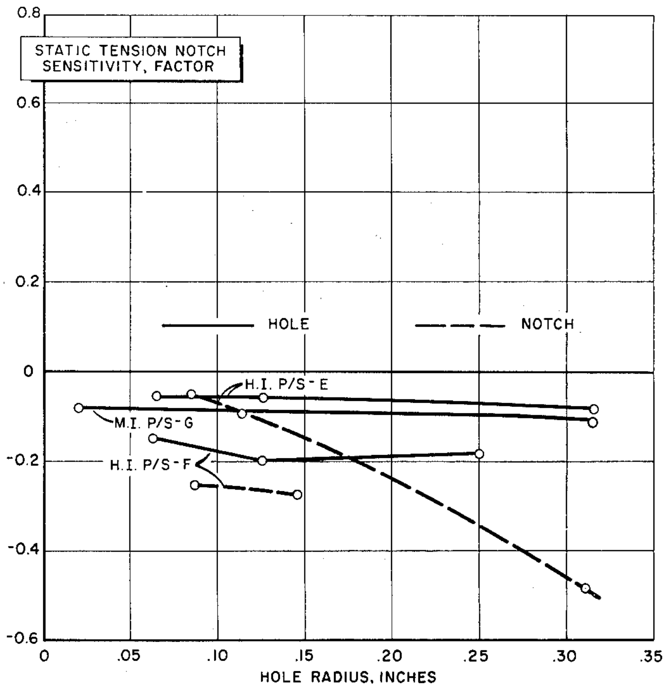

Fig. 5 Notch sensitivity of rubber modified polystyrenes at 73 deg F

decreases at a greater rate with decreasing hole size, and crosses the 73 F curve at a hole radius of about 0.10 in. Since lowering the temperature tends to inhibit flow, and cause brittle failure, it was not expected that the crossover would occur.

The unexpected effect of temperature is more dramatically shown in Fig. 3. The notch sensitivity of a second general-purpose polystyrene at three temperatures is shown. When this polymer was investigated at 125 F, it was found that the sensitivity was higher at the elevated temperature than at room temperature. An explanation may be that local heating, due to the local high strain rate, added to the already existing elevated temperature, causes a local hot spot at the discontinuity, thus lowering the tensile strength of the notched specimen. Using this lowered value in the calculation for notch sensitivity will result in a high strength-reduction factor, and consequently a high notch-sensitivity factor. As more work is generated in this and related fields it is felt that this apparent contradiction will be resolved.

The two general-purpose materials exhibit the ...e Izod impact strengths, while the material designated GP P/S-C has a higher yield strength, higher ultimate strength, slightly higher modulus and about the same elongation. Field experience with these two materials however, showed that material C would fail when a stress concentration was present before the other general purpose polystyrene designated GP P/S-D. Fig. 4 shows that the C-material is more notch sensitive. This difference in notch sensitivity eliminates the difference in tensile strength when a stress concentrator is present. The area between the D material curve and the C-material curve at the same temperature has been shaded in to assist in the comparison of notch sensitivities. The effect of temperature on these two polymers is also shown in Figs. 2 and 3.

Fig. 5 shows the notch sensitivity of two high-impact (rubber modified) polystyrenes (HI P/S-E and HI P/S-F) and one medium impact polystyrene (MI P/S-G). The E and F-samples were run with both the circular holes in the center of the bar, and semi-circular notches on the sides while the medium impact material was run with circular holes in the center. These rubber modified materials all exhibited negative notch sensitivities. Two theories have been proposed to explain this apparent anomaly. The first may be thought of as the strain-rate theory and the second, the multiaxial-stress theory.

The strain-rate theory is based on the observed increased tensile strength, with increased strain rate. Crosshead travel was held constant for all tests, but when a specimen is notched, the majority of the elongation takes place next to the notch or in the area of stress concentration. This in fact reduces the gage length by an order of magnitude, increasing the local strain rate at the notch, proportionally. The exact strain rate is yet unknown, but instrumentation is being constructed to find what it is. When this is done unnotched tensile tests will be run at this strain rate to determine the significance of strain rate.

The second consideration of why a negative notch sensitivity was observed is the stress distribution around a hole prior to rupture. It is known that the stress pattern around a hole is not uniaxial, but multiaxial. The strength reduction factor (K_r) was calculated on the basis of uniaxial tension thus introducing some error in the calculation for the rubber modified polystyrenes. Further work, it is hoped, will shed more light on this problem.

Kline (6) shows that increasing the loading rate increases the notch sensitivity of polymethyl methacrylate. He investigated crosshead velocities of from 0.02 to 6600 ipm and hole diameters of 1/32 to 1/4 in. These results show that over 200 percent increase in sensitivity may be realized by this 3.3×10^5 increase in strain rate.

SUMMARY

1 Notch sensitivity of plastics is dependent upon the strain rate, temperature, and geometry. It would also be expected that environment would change the ductility of a polymer, but tests under various environments were not included in the investigation.

2 The use of notched tensile specimens to determine differences in brittleness between polymers which have about the same conventional strength properties, correlates well with field experience.

3 Further work in this field should be carried out to investigate the apparent negative notch sensitivities of rubber modified materials, and the increase in notch sensitivity of the general purpose polystyrene at elevated temperatures.

ACKNOWLEDGMENTS

The author would like to acknowledge the help of Alvin M. Cheesbro, Jr. of the Performance and Design Section for assistance in performance of tests and sample preparation.

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